IN-FLIGHT EXPERIENCE OF THE ARCSEC ADCS IN THE SIMBA AND RADCUBE CUBESAT MISSIONS

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ABSTRACT

The Attitude Determination and Control System (ADCS) of a satellite is a crucial subsystem to control its orientation in space. Since the communication system, the power management system and the payloads depend on the attitude of the spacecraft, the ADCS affects the performance of the whole mission. As a spinoff company of the KU Leuven, arcsec developed a novel autonomous ADCS for CubeSat missions. The ADCS includes a star tracker, three reaction wheels and a set of other sensors and actuators. Currently, the arcsec ADCS has a combined 2.5 years flight heritage on the SIMBA and RadCube IOD CubeSat missions. For both missions, the ADCS passed its commissioning steps without any issues whereafter the nominal operations delivered useful in-flight experience to improve the pointing performance. One of the major advantages of the arcsec ADCS is that the software is fully reprogrammable in space. After a first software update for the SIMBA mission, the ADCS pointing performance improved up to a pointing accuracy of 1.74 degrees (1σ-interval). Moreover, the estimated attitude by the star tracker reaches a cross-boresight accuracy of 12.5 arcseconds (1σ-interval).

1 INTRODUCTION

A CubeSat contains an Attitude Determination and Control System (ADCS) to control its orientation in space. Estimation and control of the attitude is crucial to allow the satellite to point the payload to the different targets, to point the solar panels to the sun for energy supply, to aim its antennas to the ground station for communication, etc. Therefore, the ADCS itself contains various sensors to measure different environmental properties and actuators to apply torques on the satellite. Furthermore, all those components interact with each other by estimators and controllers. The combination of these software and hardware elements determines the pointing performance of the ADCS. As a spin-off company of the KU Leuven in Belgium founded in 2020, arcsec develops and sells high accuracy ADCSs for CubeSats and SmallSats.

Currently, the arcsec ADCS has successful flight heritage on board of two 3U ESA CubeSat In Orbit Demonstration (IOD) missions. The first mission is SIMBA, which stands for Sun-Earth Imbalance, and was launched on September 3rd 2020 [1]. The SIMBA mission is led by the Royal Meteorological Institute of Belgium (RMIB) and its main payload is a cavity radiometer to measure the radiation imbalance of the earth. Based on this data, crucial global warming parameters can be analyzed.

RadCube, the second mission, is led by C3S in Hungary and was launched on August 17th 2021 [2]. The goal of the RadCube mission is to demonstrate miniaturized instrument technologies that measure the space radiation environment and magnetic field strength in low-Earth orbit for space weather monitoring purposes. The arcsec ADCS is easily scaled up to accurately control the attitude of SmallSats. The software and sensors can be reused, but the torque and momentum capacity of the reaction wheels have to increase proportionally with the inertia of the satellite.

Both the SIMBA and RadCube mission require to maintain different pointing profiles (e.g. nadir, sun and deep space pointing) with sufficient accuracy to achieve accurate measurements. The 0.5U arcsec ADCS takes care of this in autonomous way and currently obtained more than 1.66 years of flight experience on SIMBA and more than 8 months on RadCube. Figure 1 shows the ADCS that is used for the SIMBA mission. First of all, this paper will briefly discuss the building and working principle of the arcsec ADCS. Subsequently, the flight experience of the commissioning steps is described followed by a performance analysis of the ADCS and its different components. Lastly, some performance improvements based on software updates are presented.

Figure 1: The arcsec ADCS (50*mm* high, 100*mm* width) for the SIMBA mission

2 ARCSEC ADCS

An ADCS functions as feedback control loop with multiple actuators and sensors. Figure 1 shows the ADCS on the SIMBA mission and Figure 2 gives a schematic overview of the components in the arcsec ADCS and their connections. Three gyroscopes, a star tracker, a coarse sun sensor consisting of six photodiodes and three magnetometers measure the state of the CubeSat or SmallSat. To obtain an overall attitude estimation, an estimator (e.g. an Extended Kalman Filter) combines the measurements from the different sensors. Therefore, it propagates the estimated attitude based on the gyroscopes, compares the measurements of the sun sensor and magnetometers to modelled data from the orbit propagator and processes the output of the star tracker camera in order to determine the attitude based on a star database. The pointing mode determines the desired attitude which can be fixed or varying during the orbit. The difference between the desired and estimated attitude determines the so called control error and is used as input of the controller. Subsequently, the controller determines the inputs of the three reaction wheels and three magnetorquers which in turn change the attitude of the CubeSat.

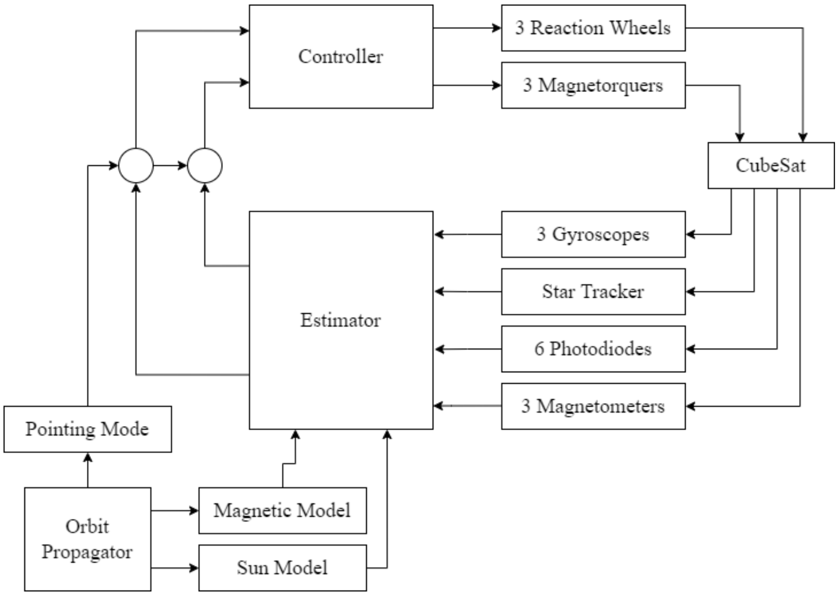

Figure 2. Schematic overview of the ADCS control loop

The ADCS tries to orient the satellite along the desired attitude, determined by the pointing mode. In the context of the SIMBA and RadCube mission, the pointing mode is almost always nadir, sun or inertial pointing. This means that a certain face of the satellite is pointed respectively towards the earth (based on the earth vector from the orbit propagator), towards the sun (based on the sun model from the orbit propagator) or towards deep space (direct input of the desired attitude). The arcsec ADCS has sufficient flexibility to point any face of the satellite along the desired vector. This is nicely illustrated during the commissioning phase of the RadCube mission. On that mission, a compact instrument suite with different payloads is located on an 80*cm* long boom away from the satellite [2]. However, when sunlight shines upon this instrument, one payload overheated and was unable to give reliable scientific results. The pointing mode was changed such that the instruments were always in the shadow of the satellite which resulted in a successful payload operation during the entire orbit.

3 COMMISSIONING

Before starting the nominal operations of a mission, every subsystem firstly has to be commissioned. The commissioning steps of the ADCS subsystem consist of high-level health and functionality tests. Only if these tests are not performing as expected, lower level tests are executed to find the cause of the problem. The high-level tests start with activating the gyroscopes, magnetometers and coarse sun sensor and checking if the raw sensor measurements corresponds with each other. In addition, the sensors are calibrated in-orbit and the satellite rotational velocity is concluded from the analysis of the sensor measurements. Secondly, the magnetorquers and detumbling controller are turned on in order to reduce the satellite rate, as shown in Figure 3 for the SIMBA mission. Thereafter, the functionality of the estimator is checked with the processed measurements and the reaction wheels are separately spun up and down. The corresponding transfer of angular momentum between the reaction wheel and the satellite is illustrated in Figure 4 during the commissioning of the reaction wheel along the satellite *x*-axis on the RadCube mission. Lastly, the star tracker imager is commissioned before including the star tracker quaternion into the control loop. After successfully going through all these tests, as is the case for both the SIMBA and the RadCube mission, the controller can be further tuned in order to obtain the best pointing performance in the nominal operations of the missions.

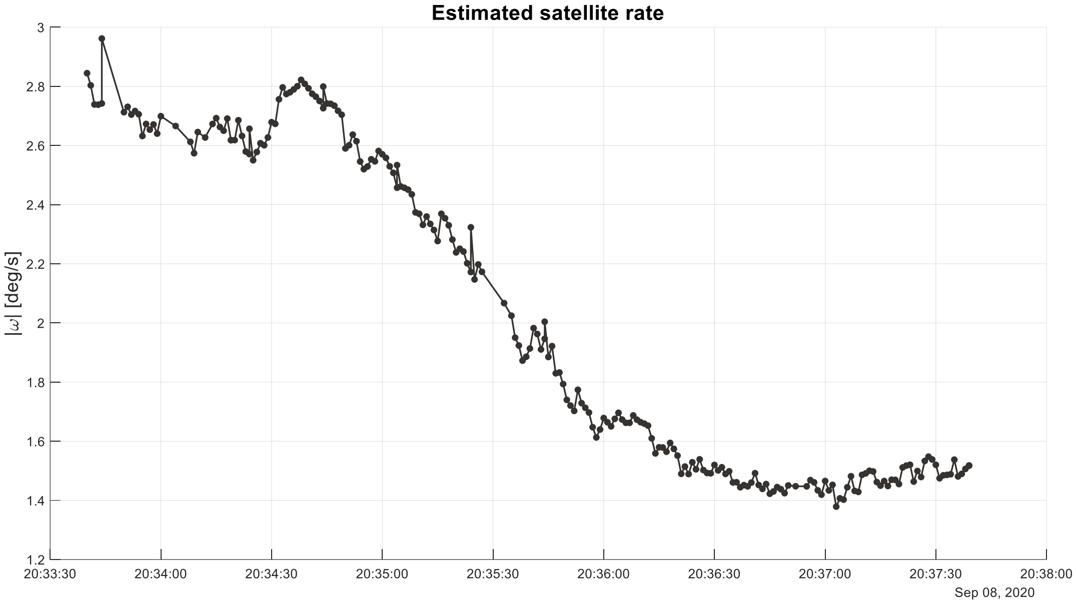

Figure 3. Decrease of the estimated satellite rate during the first detumbling on the SIMBA mission

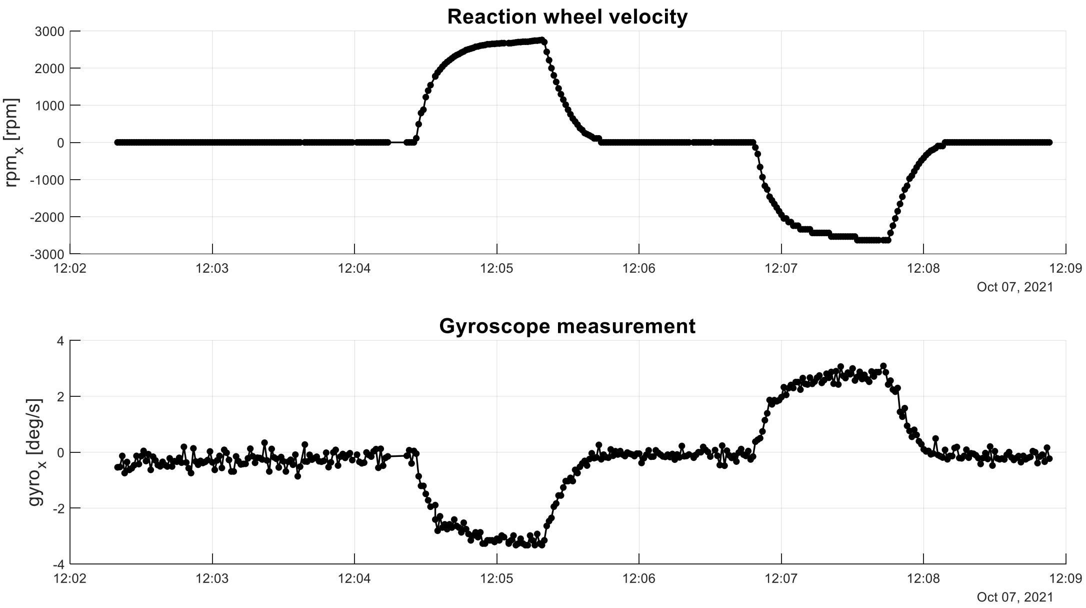

Figure 4. Raw reaction wheel velocity and processed gyroscope measurement along the *x*-axis during wheel spin up and down on the RadCube mission

4 PERFORMANCE

The objective of the arcsec ADCS is to point the CubeSat or SmallSat as stably and accurately as possible. Since the satellite contains imperfect hardware elements and disturbance torques from the space environment act on the satellite, the stability and pointing accuracy are limited. This chapter illustrates the performance of the ADCS with in-orbit data from the SIMBA mission. Firstly, the ability to detumble the satellite from high rotational rates and the availability of the star tracker, which is the most accurate sensor on board, are discussed. Subsequently, the steady-state performance in nadir, inertial and sun pointing are derived. The chapter concludes with the analysis of the transient performance during slew manoeuvres.

4.1 Detumbling controller

The detumbling controller acts as an important safety controller to avoid instability and high rotational rates. On the SIMBA mission, the performance of this controller is already tested in extreme circumstances. Figure 5 shows the angular rates around the *x*-, *y*- and *z*-axis of the satellite during the commissioning of the reaction wheels on the SIMBA mission. The rotational rate around the *x*-axis was accidently increased up to approximately 112°/*s* due to an operating error. Fortunately, the detumbling controller reduced the angular rates around the three axes back below 3°/*s* within one hour. During that hour, the *y*- and *z*-axis rates were also slightly increased (but kept below 5°/*s*) since the delivered torque of each magnetorquer causes an exchange of momentum between the satellite and two reaction wheels.

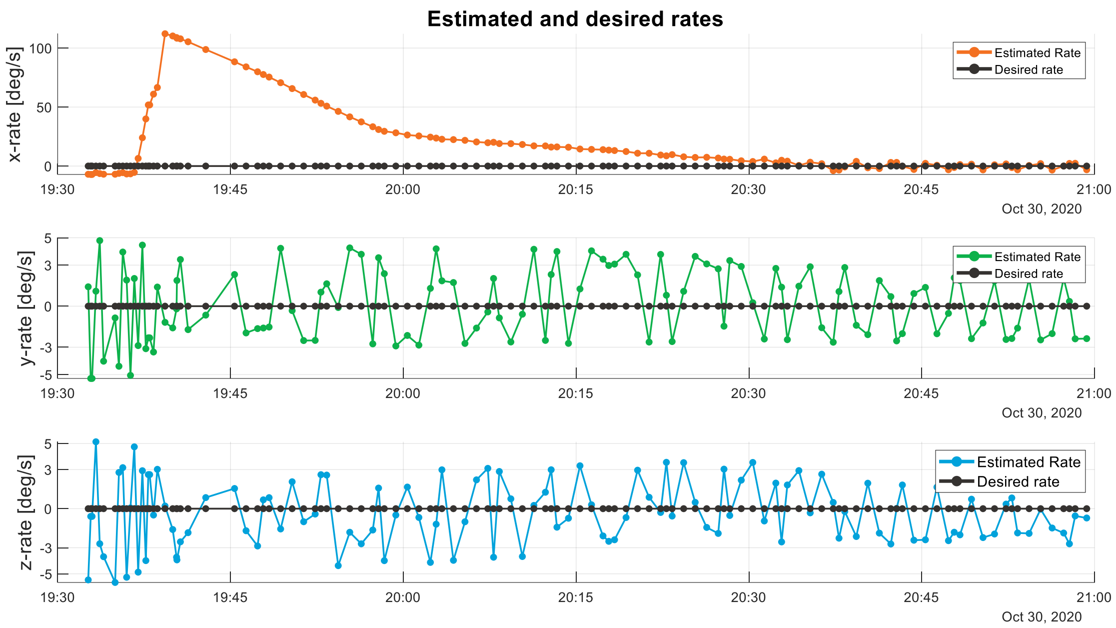

Figure 5. Estimated and desired satellite rates around the *x*-, *y*- and *z*-axis during detumbling from initially high rates on the SIMBA mission

4.2 Star tracker

The star tracker is the most accurate sensor available in the ADCS. The gyroscopes are influenced by the angular and rate random walk, the magnetometers (possibly) by the remanent dipole on the satellite and the coarse sun sensor by the indirect measurement of the sun. Moreover, the magnetometer and coarse sun sensor are compared to models of respectively the modelled magnetic field and sun vector, such that also modelling errors can influence the estimated attitude.

However, the star tracker is not always continuously available. Figure 6 shows the desired and star tracker quaternion during a few orbits of the SIMBA mission in nadir pointing. The grey boxes denote when the satellite is in eclipse. When there is no star tracker measurement available, the measurement is kept constant and is not included in the control loop. This occurs every orbit approximately fifteen to twenty minutes after the satellite exits the eclipse section of the orbit. A new star tracker measurement is again found in less than 5 minutes after entering the eclipse again. Once a star tracker measurement is available, it successfully coincides with the desired quaternion which indicates an accurate pointing of the satellite.

The unavailability of the star tracker during a large part of the daylight section can be explained by the reflections of the indirect sunlight entering the line of sight of the star tracker. For the SIMBA mission, Figure 7 shows that the edge of the borehole in the satellite panel can reflect the stray light, i.e. sun light that is not directly in the line of sight of the star tracker, into the star tracker. This results in the saturation of the image and hence in the inability to recognize stars in the image.

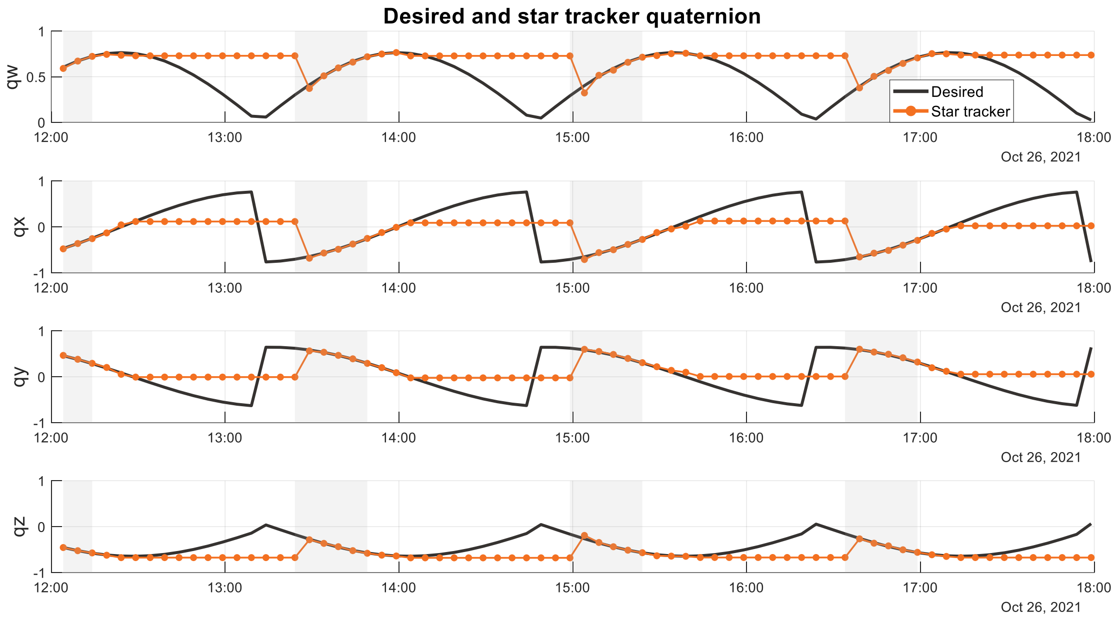

Figure 6. Desired and measured star tracker quaternion during daylight and eclipse on the SIMBA mission

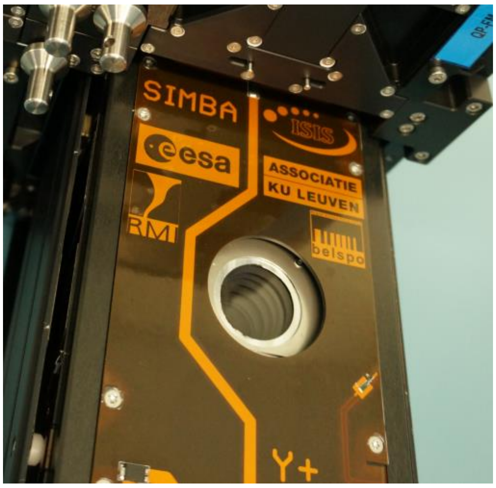

Figure 7. Location of the star tracker on the satellite close to the reflective edge of the panel on the SIMBA mission

When the star tracker is available, the cross-boresight error can be used as an indication for the attitude knowledge performance of the star tracker. Figure 8 shows the cumulative error plot of the estimated cross-boresight error during the nominal operations of the SIMBA mission. This error is estimated based on the in-orbit *x*- and *y*-coordinate centroiding error of the identified stars in the star tracker images. The conclusion of this cumulative error plot is that for 68% of the time (1σ-interval) the cross-boresight knowledge error is below 12.5 arcseconds. For 95% of the time (2σ-interval), the cross-boresight knowledge error is below 40 arcseconds. The standalone Sagitta star tracker of arcsec uses a larger version of the sensor and has more advanced processing electronics and algorithms, leading to a cross-boresight accuracy of 2 arcseconds (1σ-interval).

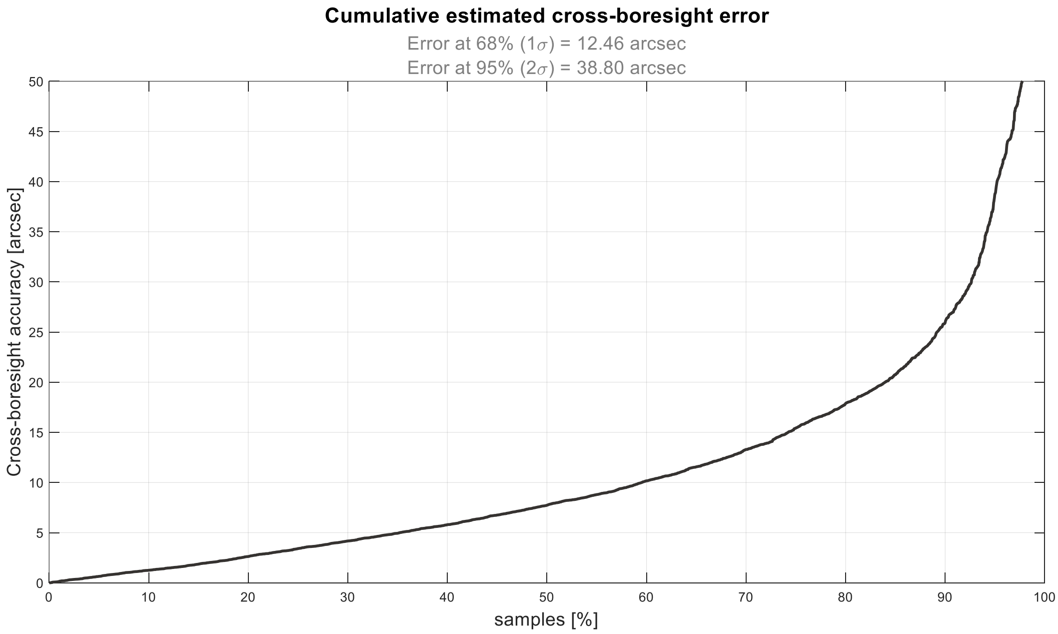

Figure 8. Cumulative estimated cross-boresight error of the star tracker on the SIMBA mission

4.3 Pointing performance

The pointing performance of the ADCS can be characterized by the control error, i.e. the difference between the desired and estimated attitude. Figure 9 shows the steady-state quaternion control error in nadir pointing on the SIMBA mission. The data segment is 101 hours long from March 12^{th} to March 17 but contains some short moments (for a few minutes) where the satellite is detumbled or the reaction wheels desaturated. At those moments, the control error increases since the satellite is not accurately controlled anymore. Furthermore, the controllability of the satellite also drops when the velocity of any reaction wheel is around zero. There, the reaction wheel friction is more nonlinear since the static friction becomes more dominant. Therefore, when a reaction wheel is at standstill, i.e. a zero-crossing, the satellite cannot be accurately controlled anymore around that axis. Additionally, the single quadrant control of the wheels, i.e. non-regulated braking or deceleration, in the current ADCS version further limits the controllability of the wheel and thus of the satellite attitude. At those moments of reduced controllability, large control peaks occur as shown in Figure 9.

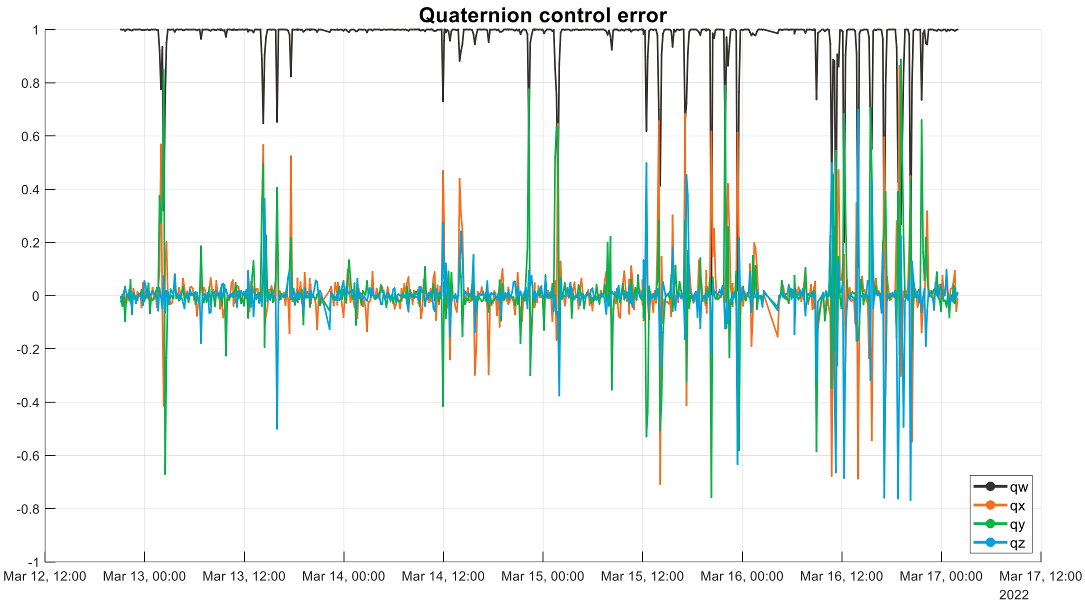

Figure 9: Steady-state quaternion control error in nadir pointing on the SIMBA mission

Figure 10 shows the cumulative Euler angles control error, i.e. the roll, pitch and yaw angle of the quaternion control error, for respectively the daylight and eclipse sections of the data segment in Figure 9. The total control error, i.e. the Euler angle error or twice the arccosine of the scalar part of the quaternion control error, is shown in the title of the figure for the 1σ-interval (68% of the data segment) in the entire data segment (overall) and separately in the daylight and eclipse sections of the data segment. The satellite is more accurately pointed (1) in eclipse than in daylight sections and (2) along the pitch and yaw axes. The former can be explained by the star tracker which returns reliable measurements for almost the entire eclipse and not during the daylight sections. The latter results from the fact that these axes have a higher inertia and are less affected by disturbance torques than the roll axis.

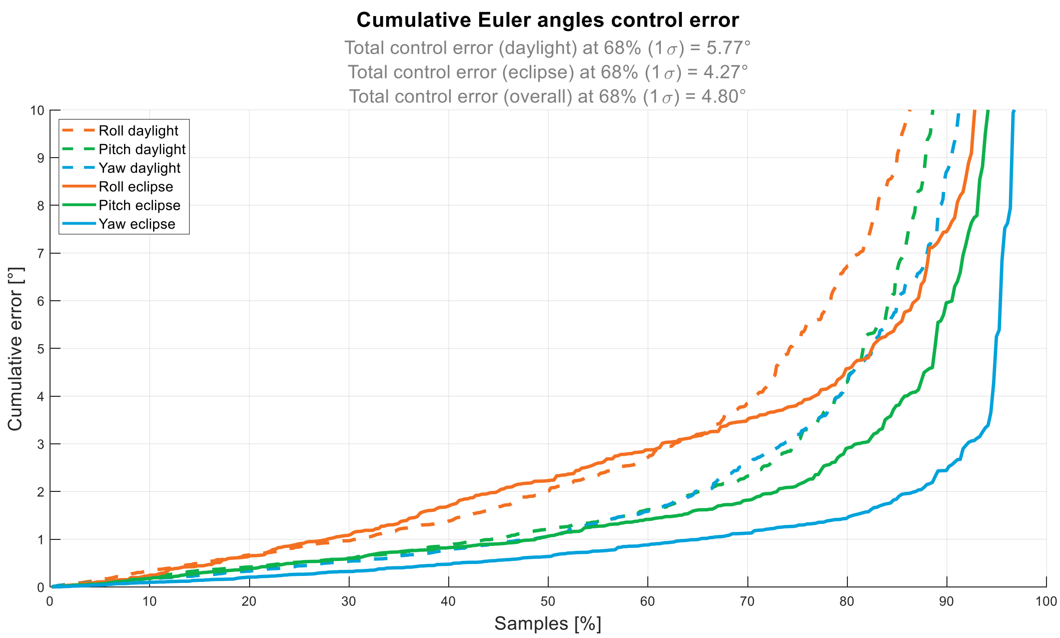

Figure 10: Cumulative Euler control error plot in nadir pointing on the SIMBA mission

Figure 11 shows the steady-state quaternion control error in inertial pointing, i.e. with a constant desired attitude over time, on the SIMBA mission. The data segment is 62 hours long from December 10th 2021 to December 13th 2021 and does not contain any periods where the satellite is detumbled or where the reaction wheels are desaturated. Compared to the nadir pointing mode where the desired attitude fluctuates significantly within one orbit, the desired attitude is not dynamic anymore and the attitude controller demands smaller torques from the actuators. Consequently, there occur almost no zero-crossings and the resulting large control error peaks are reduced. Figure 12 shows the cumulative Euler angles control error plot in inertial pointing. With respect to nadir pointing, the error in daylight is decreased by more than one degree and in eclipse even by more than three degrees for 68% of the data segment (1σ-interval). Additionally, the control error does not increase as much at higher σ-intervals, resulting in a smaller error for 95% of the data segment (2σ-interval).

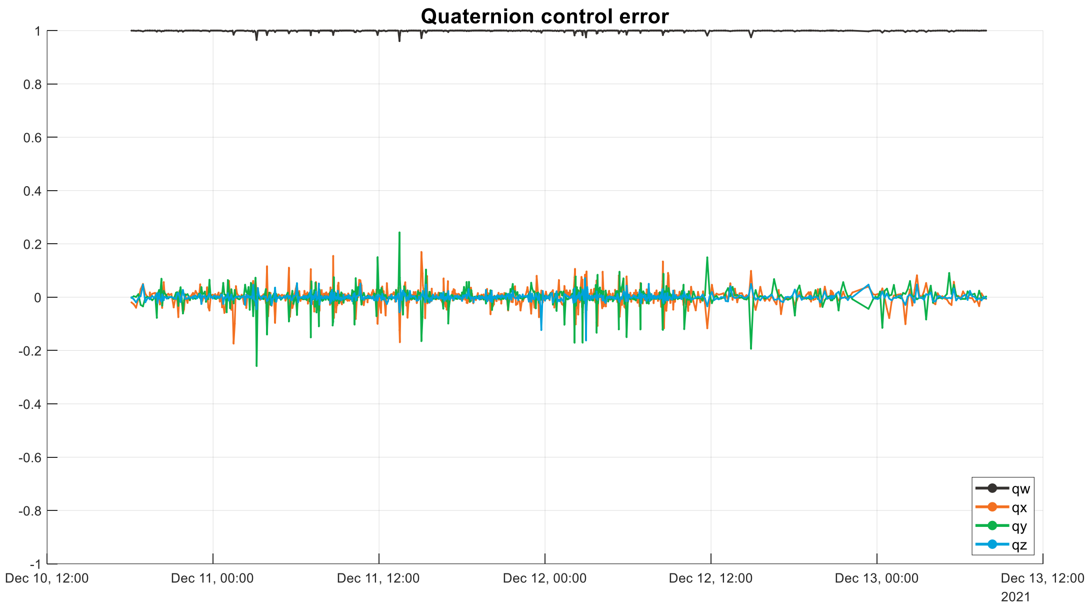

Figure 11: Steady-state quaternion control error in inertial pointing on the SIMBA mission

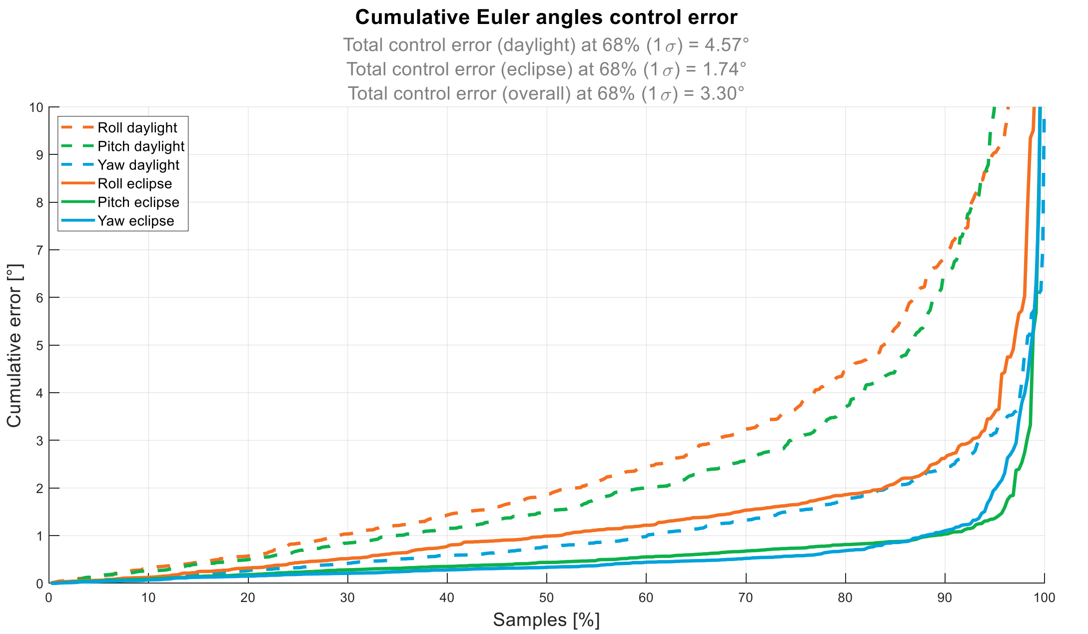

Figure 12: Cumulative Euler control error plot in inertial pointing on the SIMBA mission

Table 1 and Table 2 show the numerical values of the Euler angles control error and the total control error as shown in Figure 10 and Figure 12 for the 1σ- and 2σ-interval. Additionally, the same values are determined for a data segment of 62 hours in sun pointing mode and added to the tables. The desired attitude in sun pointing slowly varies over time with a period of one year and hence situates between nadir and inertial pointing, as is the case for the errors in the daylight section. However, in this data segment, the earth is within the star tracker line of sight due to the pointing mode and the satellite orbit. This results in a low availability of the star tracker and thus not the expected decrease of the control error in eclipse.

Table 1: Euler angles control error and total control error for 68% of the data segments (1σ-interval) on the SIMBA mission

Pointing mode	State	Roll [°]	Pitch [°]	Yaw [°]	Total [°]
Nadir	Daylight	3.658	2.178	2.324	5.768
	Eclipse	3.378	1.724	1.073	4.268
	Overall	3.462	2.002	1.586	4.799
Inertial	Daylight	3.088	2.468	1.260	4.575
	Eclipse	1.452	0.654	0.499	1.739
	Overall	2.208	1.506	0.874	3.297
Sun	Daylight	3.706	1.277	2.150	5.212
	Eclipse	3.031	2.337	1.587	4.541
	Overall	3.450	1.785	1.870	4.942

Table 2: Euler angles control error and total control error for 95% of the data segments (2σ-interval) on the SIMBA mission

Pointing mode	State	Roll [°]	Pitch [°]	Yaw [°]	Total [°]
Nadir	Daylight	34.429	27.584	24.533	55.032
	Eclipse	11.499	11.050	5.247	21.436
	Overall	29.119	23.017	17.359	48.973
Inertial	Daylight	9.045	10.290	3.154	12.987
	Eclipse	3.629	1.378	1.999	4.752
	Overall	8.062	7.748	2.997	11.846
Sun	Daylight	8.150	3.906	6.390	11.836
	Eclipse	8.069	6.191	3.846	10.490
	Overall	8.126	4.689	5.745	11.078

4.4 Slew manoeuvres

The transient performance of the ADCS is illustrated based on so called slew manoeuvres, i.e. a sudden changes in the desired attitude. They occur when the pointing mode changes (e.g. from nadir to sun pointing) or when the satellite is pointed to a different point in space during inertial pointing. Figure 13 shows the quaternion control error of a slew manoeuvre in inertial pointing with an effective slew angle of 55.29°. The experiment was designed to start in steady-state inertial pointing and to have ideal conditions for the star tracker, i.e. during eclipse and while the star tracker is pointed away from the earth. The settling time of the response is approximately 10 minutes. Figure 14 shows the desired, estimated and star tracker quaternion during the slew manoeuvre and Figure 15 shows the estimated satellite rate and the measured reaction wheel velocities. During the slew, the satellite rate increases and the availability of the star tracker decreases, as shown in Figure 14 by the periods where the star tracker measurement is kept constant. Furthermore, the velocity of the *y*-axis reaction wheel drops to almost zero around 17:36:01, while the *z*-axis reaction wheel has two separate zero-crossings at 17:39:20 and at 17:41:00. As explained before, a zero-crossing reduces the controllability of the satellite and induces oscillations from the gyroscopic effect in the quaternion control error. As the effective slew angle decreases, the attitude controller demands smaller torques from the reaction wheels. Hence, the change in the reaction wheel velocity becomes smaller and the chance of zero-crossings also decreases.

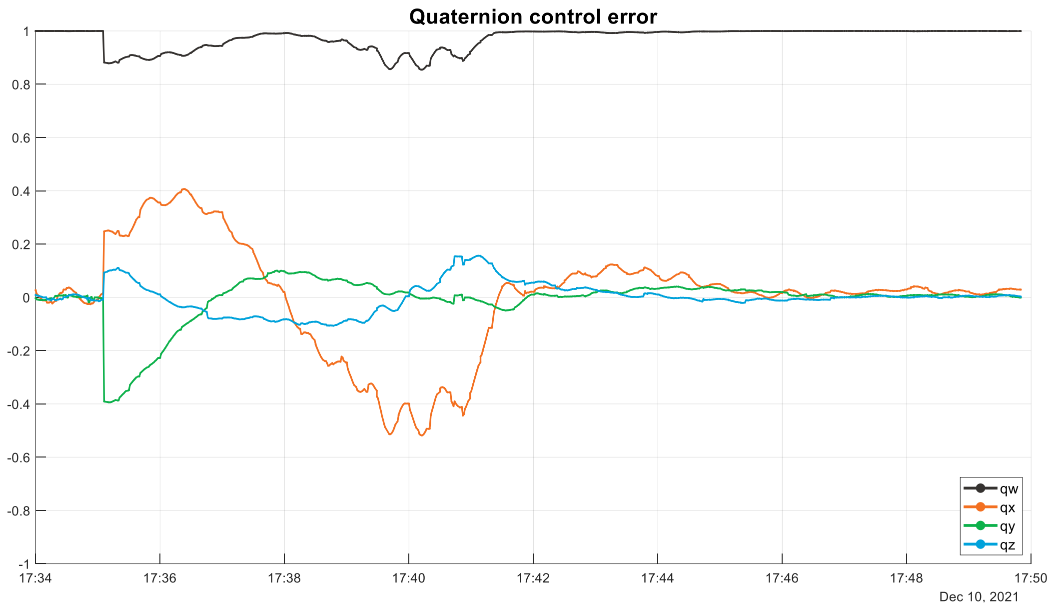

Figure 13: Quaternion control error during a slew manoeuvre on the SIMBA mission

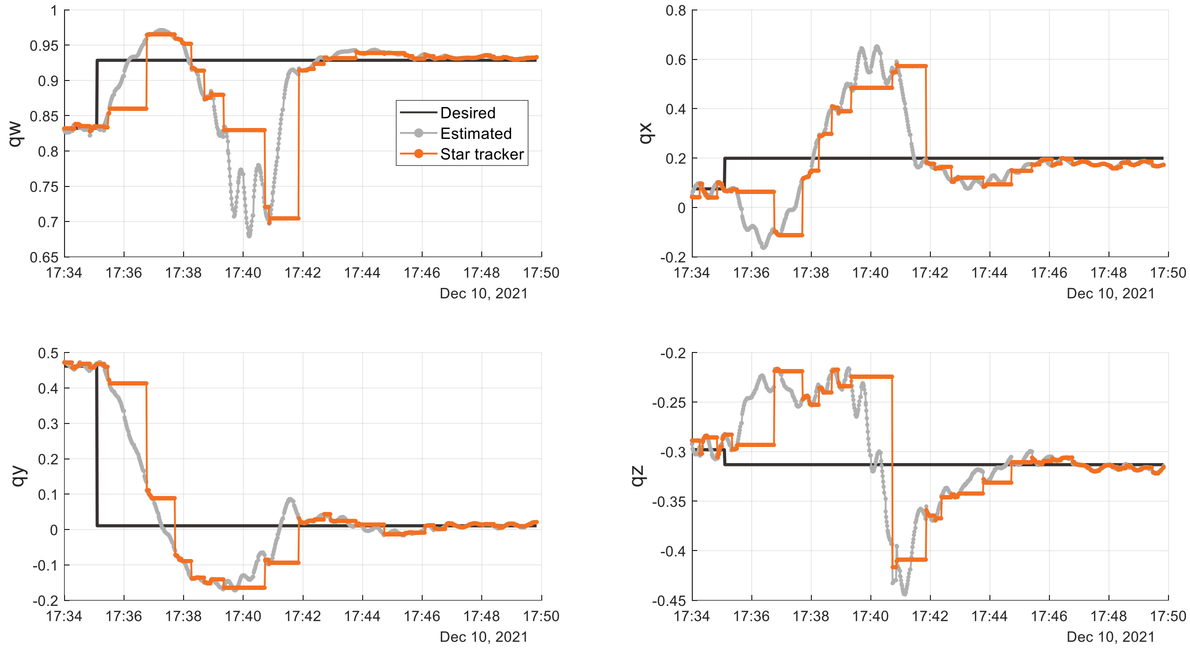

Figure 14: Desired, estimated and star tracker quaternion during a slew manoeuvre on the SIMBA mission

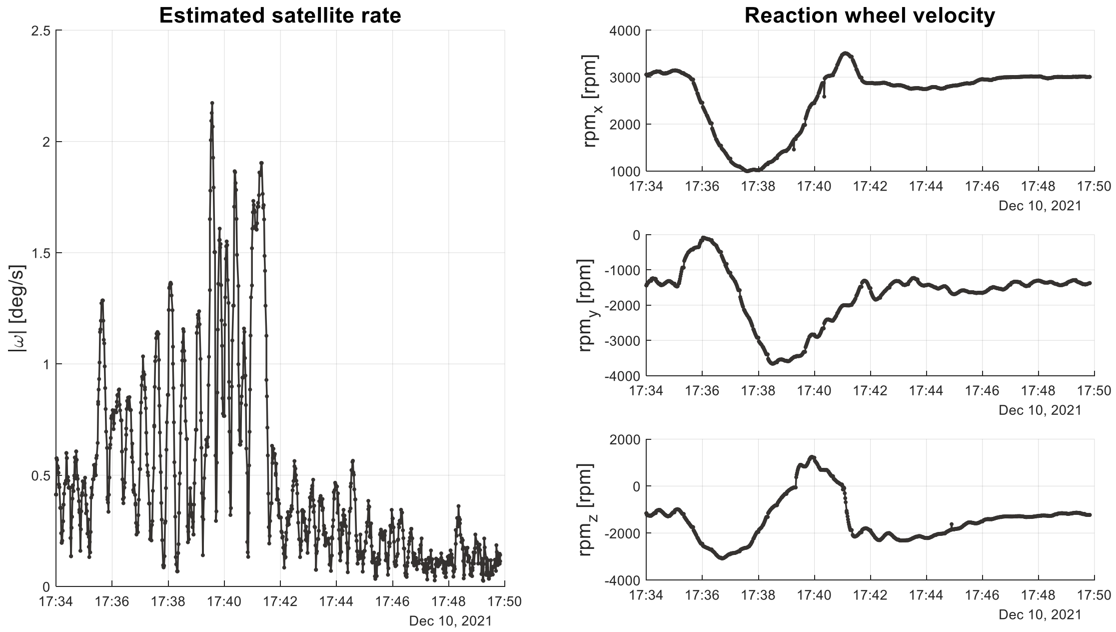

Figure 15: Estimated satellite rate and reaction wheel velocity during a slew manoeuvre on the SIMBA mission

5 SOFTWARE UPDATE

A major advantage of the arcsec ADCS is that it is fully reprogrammable in-orbit. For the two extensions of the SIMBA mission, arcsec developed a software update in order to improve the in-orbit pointing performance. The first software update took place in August 2021 and included some minor changes: new noise models in the extended Kalman filter, a new controller that decreases the bandwidth when the velocity of a reaction wheel becomes too small and some extra telemetry to enhance the tuning of the star tracker. The software update was successfully uploaded and the pointing performance improved considerably.

The second software update will take place at the end of April 2022. This update firstly includes an improved desaturation controller in order to reduce the zero-crossings on the reaction wheels. Secondly, a new estimator which is more numerically stable is implemented and some extra estimator consistency measures to tune that estimator are added. Furthermore, additional post-processing of the magnetometers is included such that variations on the remanent dipole moment of the satellite can be compensated for. Lastly, extra telemetry and controllers for the reaction wheels are incorporated since a more accurate control of the reaction wheels also improves the controllability of the satellite.

6 CONCLUSION

This paper discussed the flight experience of the arcsec ADCS on the SIMBA and RadCube missions. Both missions are currently still ongoing and have gathered a combined flight heritage of 2.5 years up till now. The ADCS successfully passed every commissioning step in both missions: from the activation and calibration of the magnetometers, coarse sun sensor and gyroscopes, the activation of the actuators to the inclusion of the star tracker in the control loop. The stability of the satellite is ensured by the effectiveness of the detumbling controller: it can decrease the rotational rate from more than 112°/s to 3°/s within one hour. The steady-state pointing performance in nadir, inertial and sun pointing is determined by a lot of factors. The first factor is the availability of the star tracker, which is influenced by the stray light of the sun, the rotational rate of the satellite and whether or not the earth is in the line of sight. Secondly, the pointing mode determines the dynamic behaviour of the desired attitude: highly dynamic with one orbit as period in nadir pointing, low dynamic with one year as period in sun pointing and constant in inertial pointing. Furthermore, the desired attitude influences the number of reaction wheel zero-crossings and the corresponding loss of controllability around that axis. These factors result in different circumstances and pointing accuracies for the ADCS, where in the best conditions (inertial pointing and eclipse) a total control error of 1.74° can be obtained.

7 REFERENCES

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